

TABLE 9. Litter and Soil Carbon Pools

Class	Nonwoody ^a		Woody		Upper soil ^b	
	Mean, g C m ⁻²	Total, Pg C	Mean, g C m ⁻²	Total, Pg C	Mean, g C m ⁻²	Total, Pg C
1	1246	21.7	1216	21.2	5291	91.9
2	1196	2.6	1135	2.5	5465	11.8
3	1345	5.3	1290	5.1	5933	23.4
4	1203	18.0	1158	17.3	5645	83.9
5	1195	7.5	1211	7.6	5635	35.3
6	869	15.5	853	15.2	3742	66.5
7	323	3.2	0	0.0	1895	18.8
8	1018	2.3	954	2.1	3915	8.7
9	274	2.7	260	2.5	1468	13.9
10	787	5.0	758	4.7	3447	21.8
11	74	1.1	146	2.2	718	10.5
12	333	8.8	0	0.0	2335	58.9
Total	93.7		80.4		445.4	

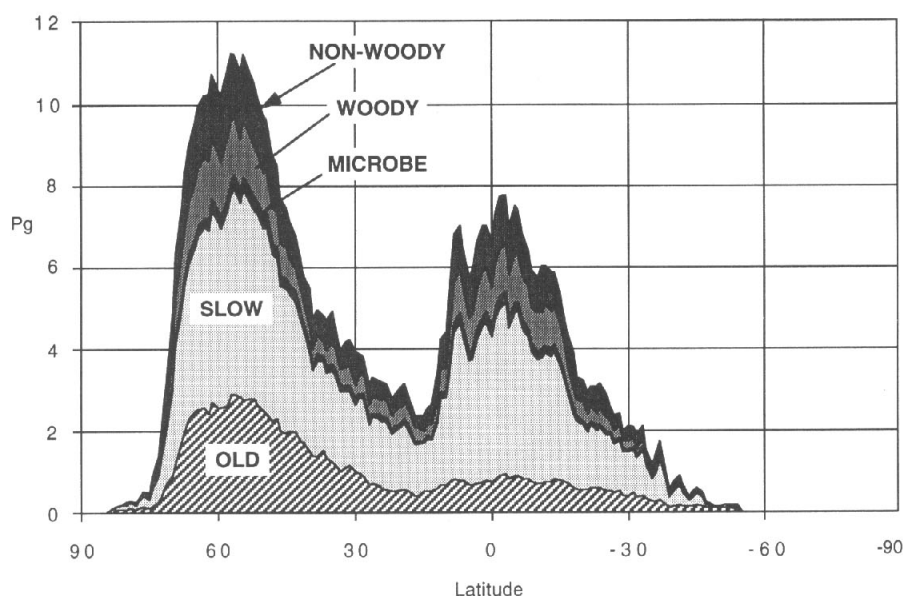
^aIncludes leaves and fine roots.^bIn top 0.3 m of profile.

Fig. 8. Latitude-based litter and soil carbon pool totals (Pg C).

Sampling Network during 1986 [Conway and Tans, 1989]. Although the atmospheric CO₂ concentration is an integrated response to terrestrial and oceanic processes, combined with the effects of anthropogenic fossil fuel and land use sources, terrestrial carbon fluxes dominate the seasonal signal [Fung et al., 1987]. Monthly changes in CO₂ concentrations (dCO₂) are roughly mirror images of

zonally averaged NEP (Figures 9a-9c). We used CO₂ measurements from Point Barrow, Alaska (BRW) at 71° N, Mauna Loa, Hawaii (MLO) at 20° N, and Christmas Island (CHR) at 2° N for comparisons to monthly NEP averaged over 50°-80° N, 10°-30° N, and 0°-10° N respectively. The latitude zones for BRW and MLO were the same as those used by Tucker et al. [1986] for a similar

TABLE 10. Turnover Times for Carbon in Four Litter/Soil Pools Shown in Figure 5

Class	Carbon Pool Turnover Time, yr			
	ML	SM	SLOW	OLD
1	0.2	0.6	9	264
2	0.9	1.6	28	815
3	1.1	1.7	32	936
4	1.3	2.1	40	1177
5	1.9	3.3	64	1873
6	0.3	0.8	13	393
7	0.6	1.2	23	679
8	0.4	0.9	16	483
9	0.5	1.1	21	611
10	1.9	4.2	84	2466
11	0.7	2.0	39	1162
12	0.7	1.1	15	457

Metabolic Litter (ML), Soil Microbes (SM), SLOW, and OLD organic matter.

analysis. For all three station locations, positive dCO_2 values were associated with transitions to consistently negative NEP, which indicates net carbon losses from terrestrial ecosystems through microbial respiration. Negative dCO_2 values were accompanied by increases in NEP to comparatively high and consistently positive values that would indicate net ecosystem carbon gains through photosynthetic fixation.

Simple linear regression of the paired monthly dCO_2 concentrations versus NEP estimates resulted in negative slopes and r^2 values of 0.67, 0.09, and 0.24 for BRW, MLO, and CHR, respectively. If a one month lag was assumed (to account for atmospheric mixing), so that NEP for month t is plotted against dCO_2 for month $t+1$, the coefficients became 0.19 for BRW, 0.52 for MLO, and 0.17 for CHR. Atmospheric circulation and boundary-level mixing effect may cause a delay of about a month in equilibrium CO_2 concentrations at MLO, which is thought to be characteristic of globally averaged CO_2 cycle [Tucker et al., 1986].

Model Result Comparisons of Production

The terrestrial production estimate from the CASA-Biosphere model of 48 Pg C yr⁻¹ is within several Pg C of previously published estimates. For example, the TEM estimate is 53.2 Pg C yr⁻¹ [Melillo et al., 1993]. Although we use some of the same calibration sites as those used in TEM for our NPP estimates, the modeling approaches are sufficiently different that continental estimates are only loosely constrained. On a continental basis, our model estimates production for North and South America at 6.1 and 14.4 Pg C yr⁻¹, respectively, compared to

TEM predictions of 7.0 [McGuire et al., 1992] and 12.5 Pg C yr⁻¹ [Raich et al., 1991]. The average CASA-Biosphere model estimate for NPP (g m⁻² yr⁻¹) in tropical evergreen forests is about 6% higher than the corresponding TEM prediction, which may explain the difference in total production for the South American continent. Differences in area estimates for the various vegetation types, however, confound this analysis.

We compared grid cell estimates of NPP from the CASA-Biosphere and MIAMI [Lieth, 1975] models. Figure 10 shows these estimates aggregated for vegetation types. The MIAMI model estimates global terrestrial NPP at around 61 Pg C, which is about 20% higher than the CASA model prediction. The lower CASA NPP estimates for many biomes may be due in part to the sensitivity of our model to IPAR. Even though the mean climate - NPP regressions developed in the MIAMI model may suggest a potential NPP for a grid cell, there can be areas within the cell where plants do not persist (e.g., surface area covered by rock, lakes or asphalt) or times of the year when human management has altered the land cover. These bare areas will lower the average IPAR for the grid cell and thus reduce the average NPP calculated in CASA for the biome type on a per square meter basis. For example, the CASA predicted NPP for class 11 (bare soil and deserts) is less than one third of the MIAMI model estimate.

Implications for Litter and Soil C Storage

The CASA-Biosphere model predicts that undecomposed litter plus carbon pools in the upper (0.3 m) soil contain about 620 Pg C, slightly more than one-third of Schlesinger's [1991] global estimate of 1500 Pg C which considers soil pools to 1.0 m depth. Our prediction of nonwoody surface litter (51 Pg C) is close to Schlesinger's [1977] estimate of 55 Pg C. The CASA prediction for standing litter pools in the tropics is somewhat higher than expected, compared to those for temperate forests (Table 9). One reason for this pattern is that overall litter decomposition rates can be underestimated using the fractionation algorithm shown in equation (16) [Parton et al., 1993], especially if the litter lignin-to-nitrogen ratio is high.

Model results (not shown here) indicate that C-to-N ratios of litter entering the soil system consistently tend toward minimum levels for all vegetation classes, except in extreme high-latitude areas. Under the present model structure, N mineralization rates are adequate to meet the maximum demands of vegetation. This pattern may result from sensitivity to the initial state of soil N pools, which follow from a spatially uniform fraction of Post et al.'s [1985] storage estimates. The overall availability of nitrogen to plant, litter, microbe and soil pools is fixed to these initial levels. Further tests involving soil N initialization levels and feedbacks on decomposition rates are underway to better understand ecosystem

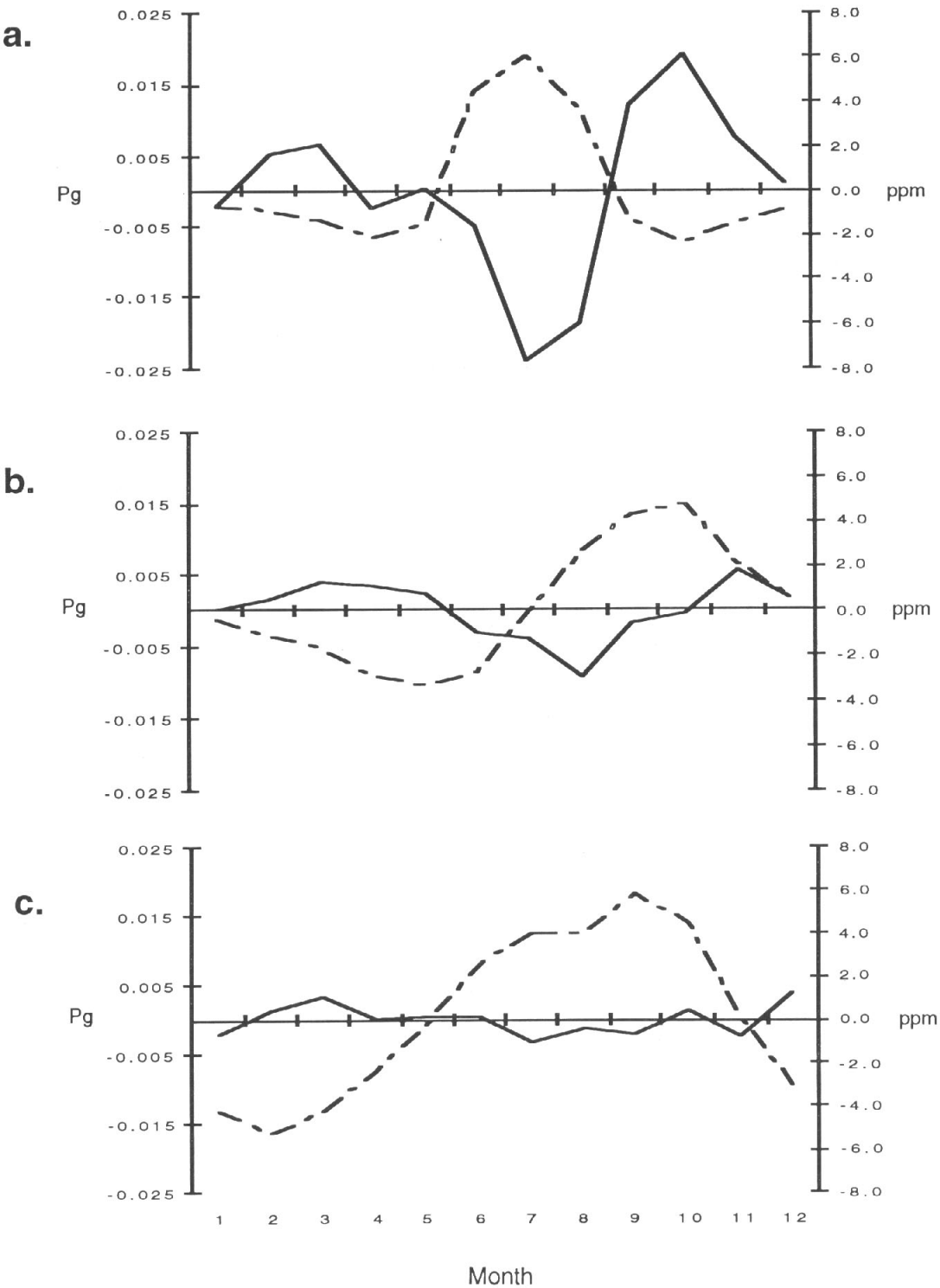


Fig. 9. Comparisons of atmospheric δCO_2 concentrations (solid lines) and NEP (dashed lines) for (a) Point Barrow, Alaska (BRW), (b) Mauna Loa, Hawaii (MLO), and (c) Christmas Island (CHR).

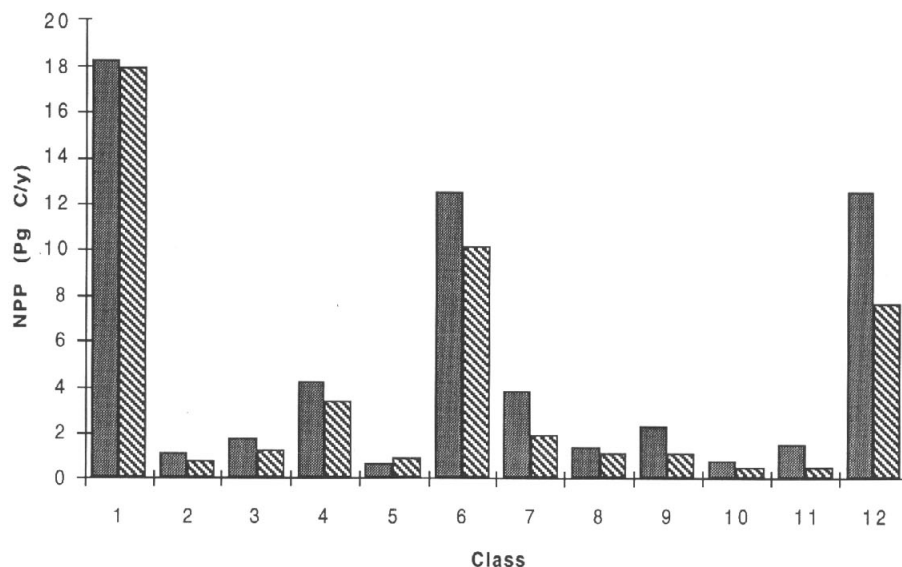


Fig. 10. Comparison of model NPP model predictions by vegetation classes from Dorman and Sellers [1989]. Shaded bars are MIAMI model [Lieth, 1975] predictions; hatched bars are CASA model (this study) predictions.

model sensitivity to nitrogen sources and sinks.

Comparison of our steady state estimates of soil carbon pools to initial model conditions, the latter of which matches the geographic distribution for life zones as reported by Post et al. [1985], indicates that the simulation predicts somewhat lower soil carbon storage at high latitudes to mid latitudes (90° - 30° N) and higher pools in tropical (20° N- 20° S) latitudes. Part of the difference may be due to the fact that we model only the upper 0.3 m of the soil, while Post et al. [1985] consider C storage to 1 m soil depth. However, if we compare the average CASA model estimate of carbon stored in upper soil layers of moist tropical forests (5.3 kg m^{-2} to 0.3 m depth) to Detwiler's [1986] estimate of 6.5 kg m^{-2} to 0.4 m depth, there is closer correspondence between observed and predicted. It should be noted, however, that the distribution of C storage in upper soil layers does not necessarily reflect soil carbon pools below 0.3 m depth. Previous comparisons suggest that the greatest difference between tropical and temperate soils is found in deep profile layers [Sanchez et al., 1982]. Our focus on the top 0.3 m soil is attributed to poor understanding of organic matter dynamics in deeper soils.

Another explanation for the prediction of relatively large soil C pools in the tropics is that 66% of all fine textured soils in the FAO-SMW are located between 30° N and 30° S [Zobler, 1986]; as pointed out by Parton et al. [1989b], the model structure used in CASA reduces the fraction of carbon lost as CO_2 during transfer to the SLOW pool in tropical soils with high silt-clay contents as per equation (18). In addition, CASA overlooks the effect of seasonal fires on reduction of soil organic matter accumulation, which may be particularly important in dry tropical areas.

The fraction of total soil carbon made up by the SLOW soil pool, which we estimate to have a residence time of 10-85 yr in most upper soil layers (Table 10), has important implications for studies of the global carbon cycle. We estimate that this fraction makes up around 65% of carbon in soil upper layers at latitudes higher than 30° N, but is as high as 83% in tropical zones. The model predicts a global SLOW pool of 300 Pg C in the surface (0.3 m) soil layers, which represents less than one third of estimated global litter and soil C storage [Houghton et al., 1990; Schlesinger, 1991]. Independent estimates using soil radiocarbon measurements of SLOW C pool size and turnover time by Harrison et al. [1993] suggested values somewhat higher than our own (75% of the total with turnover time of 25 yr, for a SLOW pool total of about 500 Pg C). Results from the CASA-Biosphere model suggest that, under a climate warming scenario, higher turnover times of relatively large SLOW carbon pools in tropical ecosystems may lead to substantial increases in CO_2 fluxes from microbial respiration, as predicted by a simpler model [Townsend et al., 1992].

Advantages and Limitations of the Model

The CASA experience shows that remote sensing and GIS technologies, when used in conjunction with large scale land data bases, can help bridge the gap in scales that exists between global biosphere models and the very local data used to calibrate them. Nevertheless, the NPP calibration process used in CASA has scaling limitations of both a temporal and spatial nature. Predictions are based on mean monthly climate data from the period 1930-1960 and remote sensing observations collected from a single

year (1987). In the calibration process, predicted NPP is compared with observations that have been gathered at various intervals over the past 30 years. The temporal discontinuity between climate, satellite and NPP site observations introduces uncertainty into CASA model estimates. Such discontinuities may be reduced in part as more satellite data become available for use in multi-year global biosphere studies. Uncertainty is also introduced into the model as a result of the difference in spatial resolution between climate/satellite data sets (~100 km) and NPP site data (with plot sizes ranging from meters to hundreds of meters). The main difficulty is that calibration sites cannot represent the heterogeneity within 1° grid cells. Features such as lakes, bare soil, and asphalt act to reduce satellite derived vegetation indices. We expect that, in general, per area regional estimates of NPP to be somewhat less than the values observed at small study sites, but the magnitude of this effect is difficult to determine without studies based on finer scale data.

Another set of limitations involves the use of a single layer soil submodel for moisture controls. First, element leaching to layers below the rooting zone was not considered in this study. Second, while the soil submodel integrates moisture availability over the top 1-2 m of soil, the scalar used to calculate carbon turnover and nitrogen mineralization fluxes applies only to the upper 0.3 m of the soil profile. Third, a single layer soil model fails to adequately account for the high efficiency with which a dry upper layer prevents evaporative loss from wetter lower layers [Hillel, 1980].

The confidence one places in model predictions depends to a large degree on reliability of input data sets. Modeling at the global scale currently necessitates use of data inputs that have not been extensively verified. This is particularly true for land use and soil data sets, where the problems involve both the density of measured sites and the consequences of aggregation to a few classes.

Models based on remote sensing data have relatively strong potential to analyze temporal changes during the era of satellite data, but their applicability to other times, climates, and biome distributions is less clear. Without additional algorithms for simulating changes in NDVI under

altered conditions, the CASA-Biosphere model has limited use for climate- or vegetation-change scenarios. Extensions and improvements in the satellite record will enhance its usefulness for detecting and quantifying global change.

CONCLUDING REMARKS

The CASA-Biosphere model links ecological regularity (e.g., the IPAR:NPP relationship) and process-level descriptions (e.g., effects of temperature and water on NPP and soil C and N transformations) with satellite and surface data at the global scale. The result has some limitations, but also some unique advantages. The use of an AVHRR-based vegetation index gives the model rich access to intra-annual and interannual variability, including some aspects of agriculture and land use change. Because the model emphasizes scaling at the process rather than the biome level, the results are only sparingly sensitive to the quality and quantity of data characterizing any single ecosystem type. This approach also tends to minimize impacts of structural and taxonomic variation within regions classified as a single biome.

Modeled global NPP is comparable to estimates from other recent models, and the seasonal pattern of modeled global NEP is consistent with the intra-annual dynamics of atmospheric CO₂. Improved validation will depend on finer scale remote sensing data and on new experimental data, concerning both ecosystem processes and the spatial and temporal distribution of atmospheric CO₂.

While the CASA approach is not ideally suited for studies of land use, atmospheric, and climate change, it can contribute to efforts along those lines. The generation of models that successfully simulates response(s) of the terrestrial biosphere to changes in land use, atmospheric CO₂, and climate will be likely to include components from diverse approaches.

APPENDIX

Major pool variables and scalars are described in this appendix. Variable definition sources include data input drivers (D), spatially uniform settings (U), and model calculations (M).

TABLE A1. Definitions for Major Pool Variables and Scalars

Name	Description	Source	Value	Units
<i>Soil Moisture Submodel</i>				
EET	Estimated evapotranspiration	M		m mo ⁻¹
PACK	Snow pack pool	M		m
PET	Potential evapotranspiration	M		m mo ⁻¹

TABLE A1. (continued)

Name	Description	Source	Value	Units
PPT	Precipitation	D		m mo ⁻¹
RDR	Relative drying rate scalar	M	0-1	unitless
SOILM	Soil moisture storage pool	M		m
T	Air temperature	D		°C
<i>NPP and Litterfall Submodel</i>				
ϵ	Light utilization efficiency	M		g C MJ ⁻¹ PAR
IPAR	Intercepted PAR	M		MJ
LT _{LAI}	Monthly litterfall fraction	M	0-1	unitless
NPP	Net primary productivity	M		g C m ⁻² mo ⁻¹
PAR	Photosynthetically active radiation	M		MJ mo ⁻¹
SOL	Solar radiation	D		MJ mo ⁻¹
T _{opt}	Temperature optimum for NPP	M		°C
T _{ε1}	Temperature stress factor	M	0-1	unitless
T _{ε2}	Temperature stress factor	M	0-1	unitless
W _ε	Water stress factor	M	0-1	unitless
<i>Soil C/N Submodel</i>				
ETX	Soil texture effect scalar	M	0-1	unitless
LFA _c	Leaf carbon allocation fraction	U	0.33	unitless
LF _l	Leaf lignin fraction	M	0-1	unitless
LM _c	Surface litter microbial C pool	M		g C m ⁻²
LM _{cn}	Surface litter microbial C-to-N ratio	U	10	unitless
LM _k	Surface litter turnover rate	U	0.455	mo ⁻¹
LM _n	Surface litter microbial N pool	M		g N m ⁻²
M _ε	Microbial C assimilation efficiency	U	0.45	unitless
MIN _n	Mineral nitrogen pool	M		g N m ⁻²
ML _c	Metabolic leaf litter carbon pool	M		g C m ⁻²
ML _{cn}	Metabolic leaf litter C-to-N ratio	U	25	unitless
ML _k	Metabolic leaf litter turnover rate	U	0.703	mo ⁻¹
ML _n	Metabolic leaf litter nitrogen pool	M		g N m ⁻²
MR _c	Metabolic root litter carbon pool	M		g C m ⁻²
MR _{cn}	Metabolic root litter M-to-N ratio	U	25	unitless
MR _k	Metabolic root litter turnover rate	U	0.781	mo ⁻¹
MR _n	Metabolic root litter nitrogen pool	M		g N m ⁻²
OLD _c	Old soil carbon pool	M		g C m ⁻²
OLD _k	Old soil carbon turnover rate	U	0.00056	mo ⁻¹
OLD _n	Old soil nitrogen pool	M		g N m ⁻²
Q ₁₀	Q ₁₀ constant	U	2.0	unitless
RTA _c	Root carbon allocation fraction	U	0.33	unitless
RT _l	Root lignin fraction	M	0-1	unitless
SL _c	Structural leaf litter carbon pool	M		g C m ⁻²
SL _{cn}	Structural leaf/root C-to-N ratio	M	150	unitless
SL _n	Structural leaf litter nitrogen pool	M		g N m ⁻²
SLOW _c	Slow soil carbon pool	M		g C m ⁻²
SLOW _k	Slow soil carbon turnover rate	U	0.0163	mo ⁻¹
SLOW _n	Slow soil nitrogen pool	M		g N m ⁻²
SM _c	Soil microbial carbon pool	M		g C m ⁻²
SM _{cn}	Soil microbial C-to-N ratio	U	10	unitless

TABLE A1. (continued)

Name	Description	Source	Value	Units
SM _n	Soil microbial nitrogen pool	M		g N m ⁻²
SRT _c	Structural root litter carbon pool	M		g C m ⁻²
SRT _n	Structural root litter nitrogen pool	M		g N m ⁻²
T _s	Soil temperature effect scalar	M	0-2.8	unitless
WDA _c	Woody carbon allocation fraction	U	0.33	unitless
WD _c	Woody detritus carbon pool	M		g C m ⁻²
WD _{cn}	Woody detritus C-to-N ratio	U	260	unitless
WD _k	Woody detritus carbon turnover rate	U	0.04	mo ⁻¹
WD _l	Woody detritus lignocellulose fraction	M	0.35	unitless
WD _n	Woody detritus nitrogen pool	M		g N m ⁻²
W _s	Soil water effect scalar	M	0-1	unitless

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